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(54) Title: SOLID STATE LASER DEVICE AND METHOD

(57) Abstract

A solid state laser (3) is provided with an adapter (11) which allows the laser (3) to be used for a variety of applications including photo-refractive keratectomy and lithography. The adapter (11) is an optical switch connected to a plurality of closely positioned light transmitting or optical fiber outputs (15) through which the laser beam passes. The optical switch (11) rapidly activates individual fibers that are preferably sequentially fired in a predetermined pattern, in order to produce a wide area laser beam or a specific pattern for surface etching.

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SOLID STATE LASER DEVICE AND METHOD

Background of the Invention

This invention relates to a solid state laser device which can be used for a variety of applications including photorefractive keratectomy and lithography. While the invention is particularly described with respect to photorefractive kerotectomy (PRK), those skilled in the art will appreciate its wider applicability for many other medical, commercial and industrial applications.

Myopia, hyperopia, regular and irregular astigmatism, and presbiopia, are all eye conditions in which the shape of the cornea prevents light from focusing on the retina. Typically, these conditions can be corrected with lenses, i.e., glasses or contact lenses. However, certain individuals cannot wear, or do not want to wear, lenses, or the lenses do not correct the corneal condition. These individuals must resort to surgery to correct the corneal condition.

One method of corneal surgery that is presently used is radial kerototomy (RK). RK is used to correct myopia. It cannot correct hyperopia or presbiopia. RK employs a scalpel to make radial incisions in the cornea, flattening the cornea to correct myopia. The blade, which is a steel or diamond blade, can damage eye tissue. RK can therefore weaken the structure of the eye and may result in unstable vision. Sometimes, its corrective effects are not permanent, and eyesight will worsen. Also, a significant amount of surgical skill is required.

A more desirable procedure is photorefractive kerotectomy (PRK) which utilizes a laser to ablate portions of the cornea. In order to reshape the corneal surface, a laser beam with a wide diameter (greater than 4

mm) must be used. Presently, only excimer lasers are capable of producing this wide beam with sufficient power to ablate the corneal surface. The laser (usually an argon fluoride excimer laser) produces a laser beam of between 4-6 mm in diameter at an ultraviolet wavelength of 193 nm to produce a fluence (energy) of 160 mJ/cm^2, the energy necessary to ablate tissue. FIG. 1 shows a functional schematic of a prior art excimer laser optical system 101 which delivers a UV laser beam to the eye E. System 101 requires anamorphic beam expanders 103, beam rotators 105, a beam monitoring system 107, and numerous other subcomponents. The laser beam must pass through several optical devices before the laser beam is passed through an iris diaphragm to ablate corneal tissue. The diaphragm is used to shape the beam to ablate corneal tissue in a desired pattern. As can be seen, the excimer laser system is very complex. This complexity is increased by the fact that many of the various subsystems must be dynamically controlled. Further, excimer lasers are very expensive and require intense maintenance. For example, the power output of an excimer laser can drop by as much as 50% in a single day unless appropriate measures, such as power ramping and rejuvenation of the gases, are taken. In any event, the gases will have to be rejuvenated periodically because they are expelled to the atmosphere after lasing. The expense of the excimer laser makes laser eye surgery very expensive and places it beyond the reach of many who may require it. In addition, only myopia and regular astigmatism can be treated with lasers at the present time.

Solid state lasers, such as diode, Nd:YAG, Erbium:YAG, or Ti:Sapphire lasers, are much less expensive to purchase and to maintain. They are also much smaller and portable, and thus can be used in smaller spaces, such

as doctors' offices. Unfortunately, a solid state laser can not produce a beam wide enough at an appropriate wavelength and energy (fluence) to conduct a PRK procedure. A Nd:YAG solid state laser operates at a wavelength of about 1064 nm. Using non-linear crystals, the frequency of the Nd:YAG laser can be quintupled, for example, to produce the necessary wavelength (213 nm) to photo-ablate corneal tissue. However, the beam is not sufficiently wide enough to perform a PRK. Currently, Nd:YAG lasers operate at around 5% efficiency after the frequency has been quintupled. Thus, although the solid state laser would be less expensive to use, it is too inefficient to provide the energy for wide area corneal ablations in laser eye surgery or other wide area etching-type functions.

Summary of the Invention

One object of the present invention is to provide a new and improved solid state laser device and method for a wide variety of applications.

A further object is to provide the aforementioned solid state laser device with an optical switch that rapidly and selectively activates a plurality of closely positioned light transmitting or optical fibers having a predetermined arrangement to produce a wide area laser beam.

Another object of this invention is to provide a solid state laser device which can perform a wide area corneal ablation for laser eye surgery.

Still another object is to provide an adapter for a solid state laser which will allow it to perform other wide area uses.

A further object is to provide such a laser device which produces a beam sufficiently powerful to photo-ablate tissue.

Still a further object is to provide such a laser device which may be used to correct a plurality of corneal conditions.

A still further object is to provide a solid state laser device and method which can be used for other medical applications as well as commercial and industrial applications.

Briefly stated, the present invention provides a solid state laser which produces a laser beam, a plurality of closely positioned light transmitting or optical fibers through which the laser beam passes, and a programmable optical switching means for selectively activating the closely positioned optical fibers in order to produce a wide area laser beam for etching a myriad of patterns of a cornea to treat specific refractive disorders or corneal pathologies. My laser device can also be used in other commercial applications where a wide area laser beam is needed, or where specific patterns must be etched on surfaces.

By utilizing the programmable switch and the bundle of fibers arranged in a set of concentric rings or other desired pattern, a wide angle effect can be achieved by rapidly switching the input energy from fiber to fiber (alternately activating and deactivating pixels) in a desired sequential fashion. The fibers are aligned so that the energy emitted from adjacent fibers (pixels) overlaps on the corneal surface, resulting in a smooth removal of corneal tissue. A suction fixation ring keeps the optical fibers well centered and holds the cable in place over the cornea during a PRK procedure.

Other objects will become apparent to those skilled in the art in view of the following disclosure and accompanying drawings.

Brief Description of the Drawings

FIG. 1 is a diagram showing a prior art excimer laser PRK system;

FIG. 2 is a diagram of the present PRK system using a solid state laser;

Fig. 3 is a diagrammatic perspective view of the solid state laser device of the present invention;

Fig. 4 is a end view of the laser device;

Fig. 5 is a schematic view showing the arrangement of optical fibers within the device;

Fig. 6 is a perspective view of the device being placed against an eye; and

Figs. 7-11 demonstrate methods of using the device for laser eye surgery.

Description of the Preferred Embodiment

The following detailed description illustrates the invention by way of example and not by way of limitation. This description will clearly enable one skilled in the art to make and use the invention, and describes several embodiments, adaptions, variations, alternatives and uses of the invention, including what I presently believe is the best mode of carrying out the invention.

Referring to the figures, reference numeral 1 is a laser delivery system or device which will deliver a wide area beam from a solid state laser. Device 1 includes a solid state laser 3 such as a diode laser, or a frequency quintupled Nd:YAG, Erbium:YAG, or frequency qaudrupled Ti:Sapphire laser, which produces a small diameter laser beam 5. Laser 3 preferably provides rapid pulses. A free-running mode laser, such as a flashlamp Nd:YAG laser or a holmium laser, has a pulse duration of 0.1-10 milliseconds and a frequency of 1-50Hz. An EO Q-switched laser provides 1-50 nanosecond pulses at 1-50 Hz and an AO Q-switched laser provides 100-200 nanosecond pulses at

1,000-5,000 Hz. A mode-locked laser, such as a Nd:YLF laser, can provide 60 picosecond pulses at the rate of 1,000 Hz.

The appropriate UV wavelengths for the laser beam can be derived via non-linear conversion in KN, KTP, beryllium boroxylate (BBO), or lithium tri-borate (LBO) crystals. These crystals have high damage thresholds, good UV transmission, low thermal birefringence, and strong non-linearity susceptibilities. They also exhibit increased reliability, harmonic efficiencies, and wide spectral transmission ranges, which make them suitable for second, third, fourth, and even fifth harmonic generation of Nd:YAG lasers.

Part of the beam 5 is directed to a beam monitor 7 using a beam splitter 9. Monitor 7 can be used to monitor the timed averaged intensity and/or spatial profile of the beam. A majority of the beam, however, is directed to a programmable light transmitting or fiber optic switch 11. Switch 11 has an input fiber 13 and an output fiber bundle 15. Beam 5 is directed into input fiber 13 by coupling optics 17. Coupling optics 17 are made from conventional refractive components which couple light into input fiber 13. Fiber 13 is preferably a UV grade silica fiber. If it has a large core (greater than 250 um) and a low numerical aperture (light acceptance cone), reasonable coupling efficiency may be obtained. Output fiber bundle 15 is made of a plurality of UV grade, multimode silica fibers 19, as can more clearly be seen in FIG 4. Fibers 19 are closely positioned, and may even be fused together. Fiber bundle 15 carries the laser beam to the eye E. The beam which is directed form the fibers of output bundle 17 has a smooth Gaussian energy profile - stronger in the center and weaker at the edges.

As is known in the art, a vacuum suction ring may be

employed to hold the laser output device to a patient's eye. In the environment of the present invention, a vacuum suction ring 21 is attached to the end of cable 15 to hold it to eye E during a PRK procedure. Suction ring 21 is attached to vacuum means, not shown, to keep fibers 19 well centered and to hold the cable 15 in place over the eye's cornea 23 during the procedure. Suction ring 21 is placed on the eye. The placement of the suction ring is shown by the shaded area 24 in FIG. 6.

Light transmitting or optic fibers 19 are preferably arranged in circles, adjacent each other. There are sufficient number of circles to cover the cornea of the eye. Cable 15 is thus approximately 12 mm in diameter, the largest diameter of the human cornea. In FIG. 5, I show twelve concentric circles, a-l, corresponding to the circles of fibers 19. In order to meet the geometric arrangement requirements, fibers 19 may have to be arranged in a grid, rather than a radial pattern. In either case, selectively firing the optical fibers rapidly and in a desired sequence, as described below, produces a wide area laser beam pattern using the narrow laser beam of a solid state laser.

By using optical switch 11 to rapidly switch between the various fibers 19 through which the laser beam passes, a wide area effect can be achieved, without actually using a wide area beam. Each laser pulse is applied through each optical fiber in rapid succession. The fibers are fixed and aligned so that the laser pulses overlap each other on the corneal surface. Thus, through the use of my device, the narrow beam of a solid state laser can be converted into a predetermined pattern such as a wide area laser beam or a specific pattern to be etched on a surface.

As stated above, the laser beam is received by input

fiber 13. Switch 11 switches the output fibers 19 through which the laser beam passes. Presently available switches can handle up to one hundred (100) separate output fibers 19. This is sufficient to cover most small surfaces, such as corneas. However, if more fibers are required, a configuration can be achieved by "ganging" four fibers together and imaging the beam on these fibers to effectively form a 4x400 switch. Switch 11 typically operates up to 50 Hz (50 switches/second), although the light transmitting fibers can accommodate higher switching speeds, when technically available. This allows the switch to easily pass each pulse from the laser through a different fiber 19.

Switch 11 is programmable and can fire fibers 19 in a desired pattern. Switch 11 is controlled by a computer 25 which sends input to, and receives information from, switch 11 over a communication line 27. Switch 11 is preferably an asynchronous switch which is triggered by the pulse signal of the laser 3. Therefore, computer 25 communicates with laser 3 over a communication line 29. By entering the appropriate pattern into computer 25, it will cause switch 11 to vary the output fibers 19 through which beam 5 is directed.

A fixation source 31 may be used to align the optical axis of fiber bundle 15. This allows the operator to align eye E to device 1. Fixation source 31 may be either an LED or low power semiconductor laser. A mirror 33, placed between coupling lenses 17, directs beam 35 of fixation source 31 into switch input fiber 13. Mirror 33 allows beam 5 of laser 3 to pass through.

Corneal topographic devices 37 and 39 are provided to supply information to computer 25. Devices 37 and 39 are preferably rastrophotogrammetry output and input sensors, respectively. These sensors analyze or measure the

strength of the cornea during the PRK procedure and are connected to the computer 25 for instantly calculating the amount of corneal tissue that has been ablated.

An "A" scan ultrasonographic device 41, coupled to a probe 43, is provided to measure the length of the eye prior to a PRK procedure. Probe 43 rests on the eye on the center of the cornea prior to the procedure and then is moved away.

By using the rastrophotogrammetry sensors 37 and 39, along with "A" scan ultrasonigraphic and a preoperative refraction, the corneal power requirements for emmetropia (focusing of light on the retina) are calculated instantaneously.

Turning to figures 7a-11, the method of using my laser device will be explained. In referring to the position of the fibers, clock positions will be used; i.e. 12:00 fibers, 3:00 fibers, etc., in conjunction with the circle a-l in which the fiber is located.

Figure 7a shows a myopic (near sighted) eye. Light rays L are shown to focus in front of the eye's retina. The correction of the myopic eye is shown in Fig. 7b, by shaded area 47, in which material from the center of the cornea is removed to flatten the cornea. To treat myopia using device 1, switch 5 is programmed to fire the 12:00 fiber in circle f first. The adjacent fibers are then fired in a clockwise progression in circle f in a sequential fashion until the 12:00 position in the circle is reached. It will be noted that starting at the 12:00 position is preferred, however, the operation could be started at any position. This pattern of operation is then repeated for circles e, d, c, b, and a, in that order. To achieve a concave effect, the entire sequence is repeated starting at the circle e and progressing in the same pattern firing the fibers of circles d, c, b and

a. The pattern is repeated four more times, each time reducing the number of circles which are fired. Stated differently, in the first round, all circles f-a are fired, in the second round, the fibers of circles e-a are fired; then the fibers of circles d-a; then the fibers of circles c-a, etc., until the fibers of circle a are fired. This pattern of operation will tend to form a concave area in the cornea which will allow light rays to focus on the retina.

A farsighted, or hyperoptic, eye is shown in Fig. 8a. Light rays L are shown to focus behind the eye's retina. In Fig. 8b, the corneal material is shown removed from the outer areas of the cornea, as at 49, to steepen the cornea. To treat hyperopia using device 1, switch 5 is programmed to fire the 12:00 fiber in circle f first. The adjacent fibers are then fired in a clockwise progression in circle f in a sequential fashion until the 12:00 position in the circle is reached. This pattern of operation is then repeated for circles g, h, i, j, k, and l in order. To achieve a concave effect, the entire sequence is repeated starting at the circle g and progressing in the same pattern firing the fibers of circles h, i, j, k, and l. The pattern is repeated five more times, each time reducing the number of circles which are fired, as was done above in treating myopia. Stated differently, in the first round, all circles f-l are fired, in the second round, the fibers of circles g-l are fired; then the fibers of circles h-l; then the fibers of circles i-l, etc., until the fibers of circle l are fired. This pattern of operation will tend to form a convex area in the cornea which will allow light rays to focus on the retina.

As can be seen by the forgoing, by programming switch 11 to fire fibers 19 in a desired order or pattern,

corneal tissue can be removed in a desired pattern. Referring to Figs. 9 and 10, regular and irregular astigmatisms are noted by steepened corneas along the corneal meridian. In Fig. 9, a regular astigmatism is shown with the steepened cornea, as at 51, along the 12:00 meridian and in Fig. 10, an irregular astigmatism is shown with steeper hemimeridians, as at 53, at the 3:00 and 12:00 meridians. The astigmatisms are treated with device 1 by firing the fibers 19 along the meridians which lie over the steepened area. In Fig. 9, the optical fibers along the 12:00 meridian can be fired so that the underlying cornea flattens within the 6mm zone (circle f) or, the optical fibers peripheral to the 6mm ring can fire along the 3:00 position to steepen the 3:00 meridian of the cornea. In Fig. 10, the irregular astigmatism can be treated by determining the topography of the cornea which can be programmed into the optical switch 11 so that irregular raised areas of the cornea can be sequentially removed. The rastrophotogrammatic devices 37 and 39 can be used to perform this function.

Presbiopia is shown in Fig. 11. Presbiopia is a condition commonly occurring in those over age 40 and is noted by the inability to see things close up. Presbiopia can be treated with device 1 by firing peripheral fibers near the 6 o'clock position to steepen the inferior peripheral cornea, shown at 55. This creates a bi-focal effect.

Presbiopia can also be treated with the use of diffractive lenses. Switch 11 can be programmed to fire fibers 19 to etch the cornea into a diffractive lens.

In view of the above, it will be seen that principles of my invention have applications beyond ophthalmological use. For example, integrated circuits of chips, such as computer chips, are currently etched using excimer

lasers. The pattern of the circuits could be programmed into my switch 11 and the solid state laser 3 could thus be used here. The device 1 can also be used in other fields where laser etching or lithography is used. These various applications may only require a modification in the number, arrangement and/or sequence of firing the output fibers 19 of switch 11. All of these examples are merely illustrative of the many applications to which the present invention may be directed.

WHAT IS CLAIMED IS:

1. A solid state laser device including a solid state laser which produces a laser beam, a plurality of closely positioned light transmitting fibers through which the laser beam passes, and optical switching means for selectively activating the closely positioned light transmitting fibers in order to produce a predetermined pattern on a surface.

2. The device of claim 1 wherein there are sufficient number of said light transmitting fibers to cover a predetermined area.

3. The device of claim 2 wherein the plurality of closely positioned light transmitting fibers are located in a predetermined arrangement of concentric circles.

4. The device of claim 2 wherein said closely positioned light transmitting fibers are arranged in a grid pattern.

5. The device of claim 1 wherein said switching means includes an input fiber through which said laser beam passes to direct the beam into said switching means for selectively directing said laser beam through said closely positioned light transmitting fibers.

6. The device of claim 5 further including coupling means for introducing said beam into said input fiber.

7. The device of claim 1 wherein said switching means is programmable.

8. The device of claim 1 including computer means for controlling activation of said light transmitting fibers.

9. The device of claim 8 wherein said computer means is operatively connected to both said switching means and said laser.

10. The device of claim 1 wherein the adjacent closely positioned light transmitting fibers are arranged

to provide overlapping laser pulses on the surface to be treated.

11. An optical switch for a solid state laser including an input light transmitting fiber which receives a laser beam from said laser and a plurality of output light transmitting fibers, said optical switch interconnected to means for selectively activating the output fibers through which said laser beam passes.

12. The optical switch of claim 11 wherein said switch is programmable.

13. The optical switch of Claim 11 wherein said means for selectively activating the output fibers comprises computer means.

14. The optical switch of claim 11 wherein said switch can selectively activate the output light transmitting fiber through which said laser beam passes in less than 5 nanoseconds.

15. The optical switch of claim 14 wherein said switch can process 1000-3000 switches/second.

16. An adapter for a solid state laser device to selectively convert individual laser beams emanating from light transmitting fibers connected to said laser device into a collective predetermined laser beam pattern on a surface to be treated.

17. The adapter as defined in claim 16 wherein said light transmitting fibers are arrayed in a predetermined pattern to provide overlapping laser pulses on the surface to be treated.

18. The adapter as defined in claim 16 wherein the light transmitting fibers are aligned to enable energy emitted from adjacent fibers to overlap on the surface to be treated.

19. The adapter as defined in claim 16 wherein said adapter comprises a programmable optical switch for

selective activation of said light transmitting fibers in a desired sequence.

20. The adapter as defined in claim 19 including means for analyzing the surface being treated by the wide area laser beam, and means for modifying the selective activation of said light transmitting fibers based on the information received from said analyzing means.

21. The adapter as defined in claim 16 wherein said adapter is connected on one side to a single input fiber and to a plurality of light transmitting output fibers on another side of said adapter.

22. A solid state photorefractive kerotectomy (PRK) laser device including a laser which produces a wide area beam pattern from closely positioned light transmitting fibers, in order to treat a plurality of corneal conditions.

23. The PRK device of claim 22 including a switching device having an input fiber which receives a laser beam from said laser, said laser beam being passed through said closely positioned fibers one at a time, in rapid succession, to produce said wide area beam pattern.

24. The PRK device of claim 23 wherein said switching means is programmable and can fire the output fibers in any desired pattern.

25. The PRK device of claim 24 wherein there are sufficient numbers of said output fibers to produce a wide area laser beam that covers a cornea.

26. The PRK device of claim 25 wherein said fibers are arranged in concentric circles.

27. The PRK device of claim 25 wherein said output fibers are arranged in a grid pattern.

28. The PRK device of claim 24 and further including intraoperative corneal power measuring means comprising rastrophotogrammetry means to measure eye corneal strength

and "A" scan ultrasonographic means for measuring the axial length of an eye.

29. The PRK device as defined in claim 28 wherein at least the rastrophotographic means feeds information into the switching device for instantaneous programmable adjustment thereof.

30. A method for performing photorefractive kerotectomy using a solid state laser which produces a laser beam and a programmable switch that receives said laser beam and directs said beam through a plurality of output fibers, one at a time, in a desired programmed pattern, the method including programming said switch to fire said fibers in a desired laser beam pattern to photo-ablate desired portions of the cornea and operating said laser.

31. The method of claim 30 wherein the output fibers are arranged in a pattern approximating a plurality of circles adjacent each other, said method comprising firing the fibers from a middle circle in a sequential pattern and firing the fibers of inner circles inside of said middle circle in a sequential pattern, one circle at a time when used to treat myopia.

32. The method of claim 31 and further including repeating said steps for said inner circles.

33. The method of claim 32 wherein said method further includes successive firing of the fibers of said inner circles such that the area of said fired fibers is reduced with each successive round of firing.

34. The method of claim 30 wherein the output fibers are arranged in a pattern approximating a plurality of circles adjacent each other, said method comprising firing the fibers from a middle circle in a sequential pattern and firing the fibers of outer circles outside of said middle circle in a sequential pattern, one circle at a

time to produce an annular pattern when used to treat hyperopia.

35. The method of claim 34 further including repeating said steps for said outer circles.

36. The method of claim 35 wherein said method further includes successive firing of the fibers of said outer circles such that the size of said annulus is increased with each successive round of firing.

37. The method of claim 36 wherein the output fibers are arranged in a pattern approximating a plurality of circles adjacent each other, when used to treat astigmatisms comprising firing the fibers which are aligned over the corneal tissue to flatten said cornea.

38. The method of claim 37 and further including mapping said corneal topography when said astigmatism is an irregular astigmatism; said programming step including programming said switch in accordance with said mapping.

39. The method of claim 30 wherein the output fibers are arranged in a pattern approximating a plurality of circles adjacent each other, said method, when used to treat presbiopia, comprising firing the fibers over the inferior peripheral cornea to steepen said inferior peripheral cornea.

40. The method of claim 30 wherein the output fibers are arranged in a pattern approximating a plurality of circles adjacent each other, said method, when used to treat presbiopia, comprising firing the fibers over the inferior peripheral cornea to etch the cornea into a diffractive optical lens.

41. A method for etching a pattern on a surface using a solid state laser which produces a laser beam and a programmable switch which receives said laser beam and outputs said beam through a plurality of output fibers, one at a time, in a desired programmed pattern, the method

including programming said switch to fire said fibers in a desired pattern and operating said laser.

42. A programmable, multi-channel ascynchronous fiber optic switch which is computer controlled to a synchronous repetition rate of a laser device output

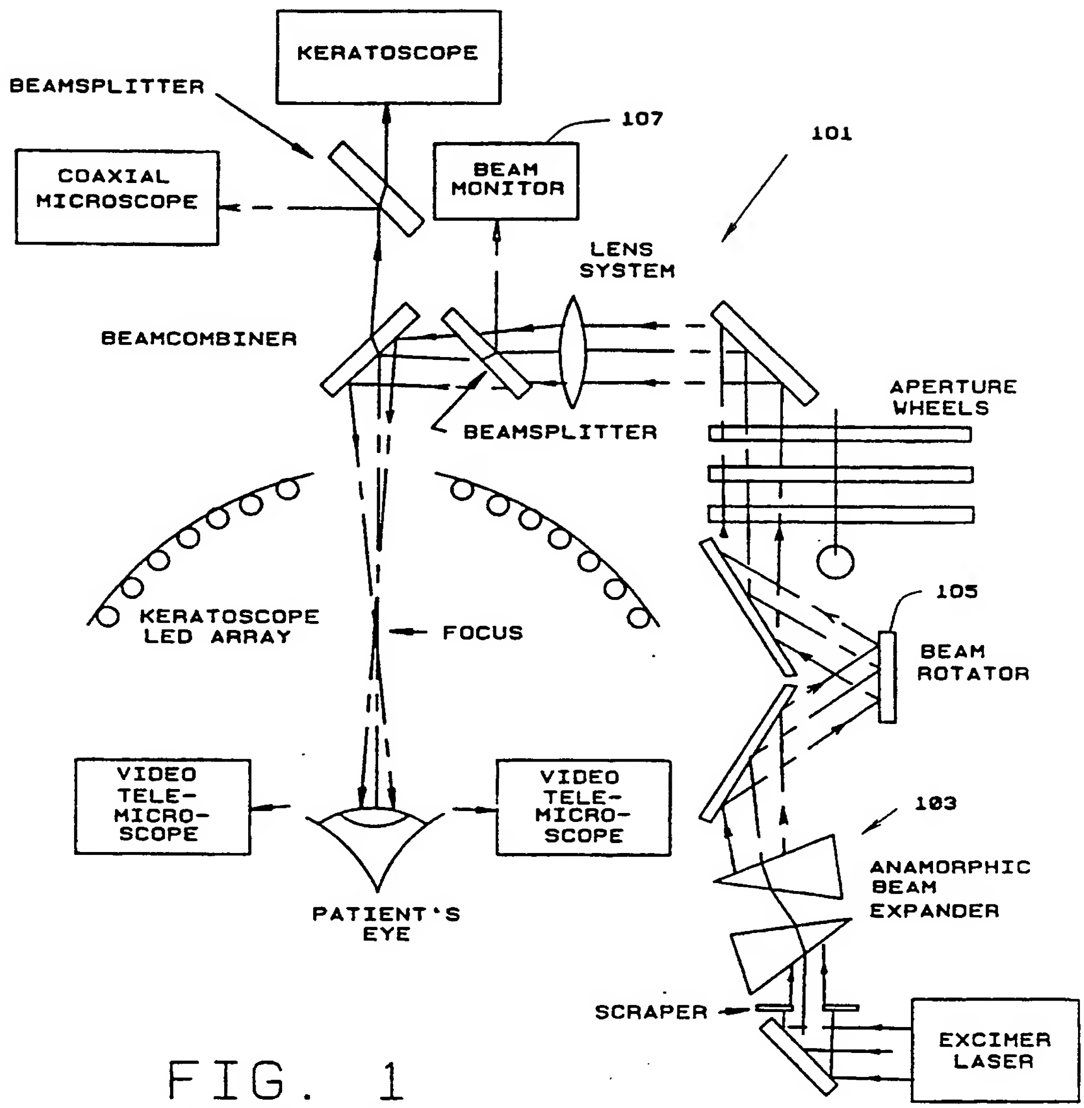
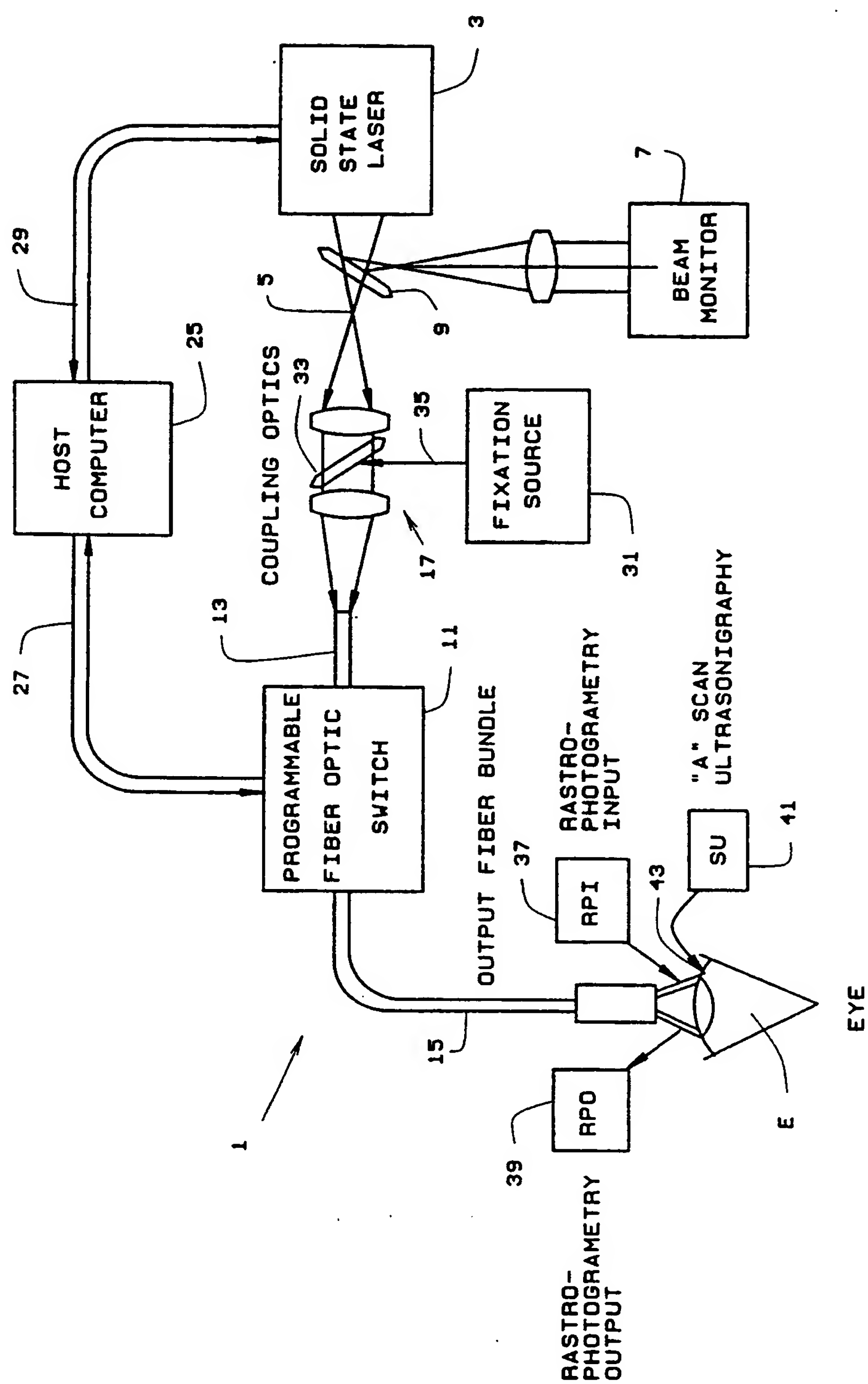


FIG. 1
PRIOR ART


SOLID STATE LASER
3
7
BEAM MONITOR
5
9
29
25
HOST COMPUTER
COUPLING OPTICS
33
35
FIXATION SOURCE
17
31
13
11
27
PROGRAMMABLE FIBER OPTIC SWITCH
OUTPUT FIBER BUNDLE
RASTRO-PHOTOGRAMETRY INPUT
"A" SCAN ULTRASONIGRAPHY
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RPI
43
SU
41
15
EYE
E
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RASTRO-PHOTOGRAMETRY OUTPUT

FIG. 2

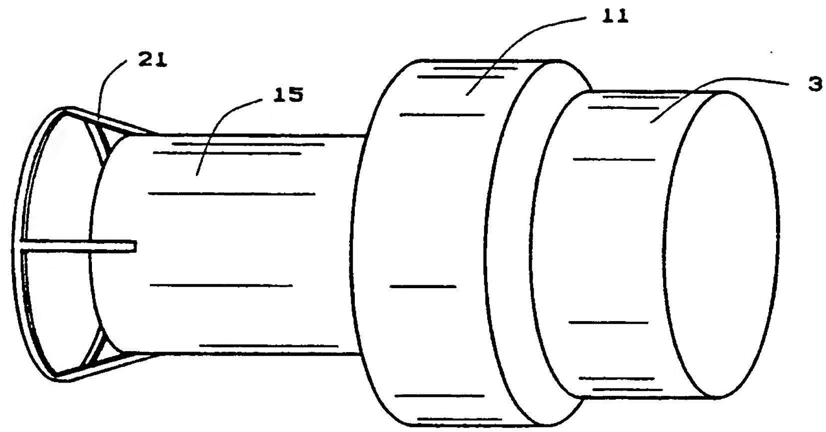

FIG. 3

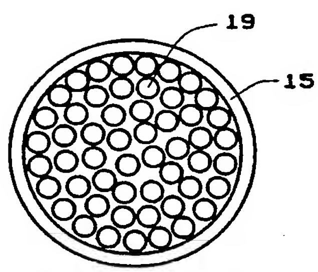

FIG. 4

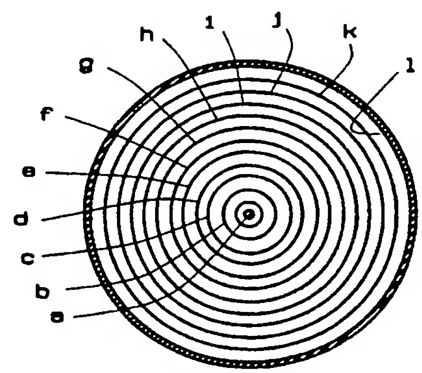

FIG. 5

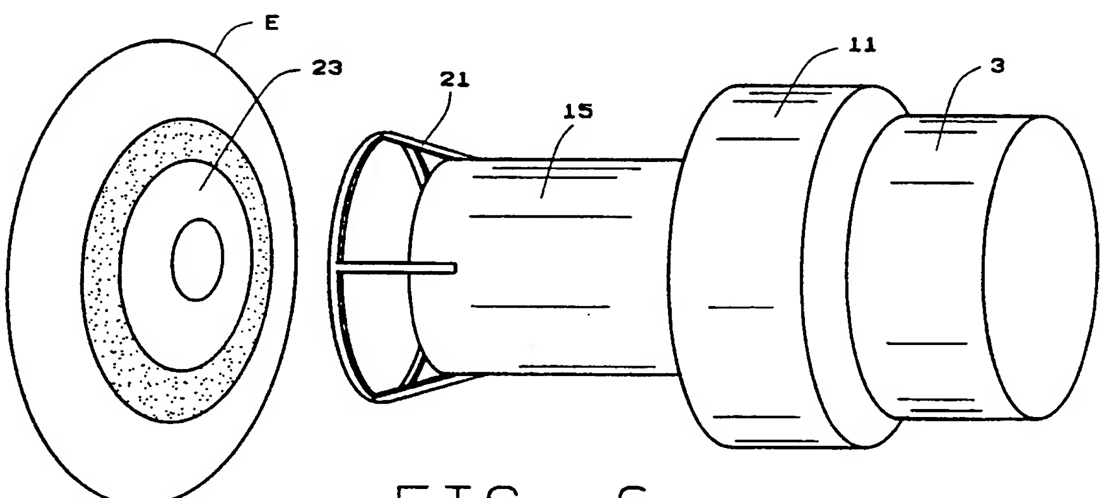

FIG. 6

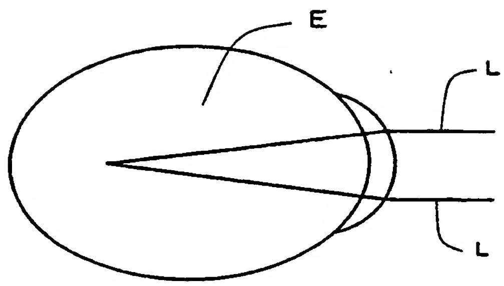

FIG. 7a

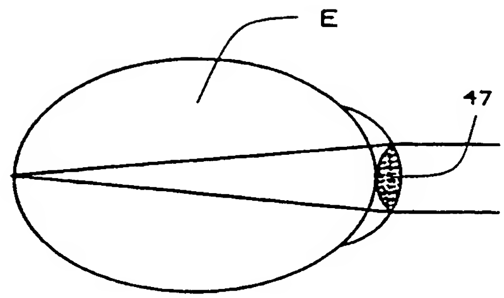

FIG. 7b

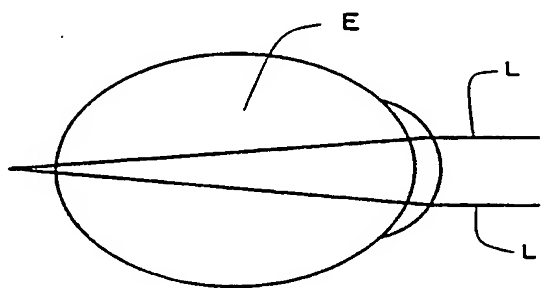

FIG. 8a

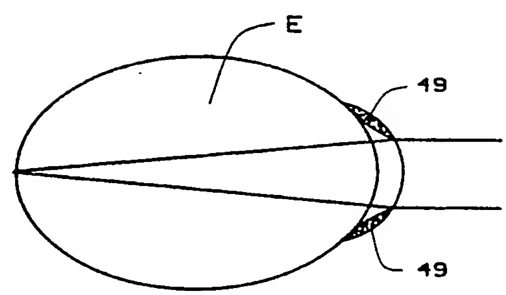

FIG. 8b

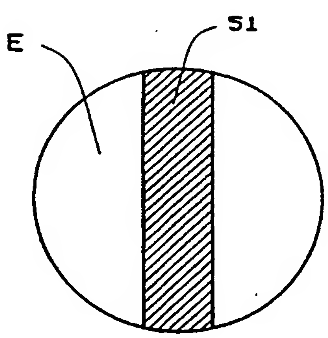

FIG. 9

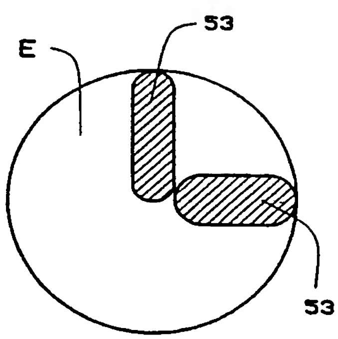

FIG. 10

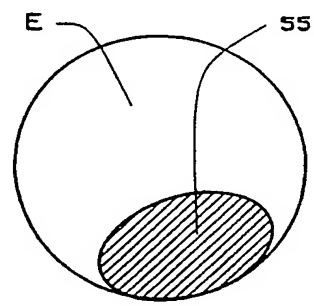

FIG. 11